Assessment of liquefaction occurrence conditions in Quaternary marine sands: case study of the November 26, 2019 earthquake in Durrës (Albania)

Denis Moiriat, Edward Marc Cushing, Celine Gelis, Aida Tasellari

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Denis Moiriat[1], Edward Marc Cushing, Céline Gélis

IRSN Institut de Radioprotection et de Sûreté Nucléaire

Aida Tasellari

Trema Engineering

ABSTRACT

The Albanian earthquake of November 26, 2019 with M_w magnitude of 6.4 caused severe impacts in Durrës city built above a Plio-Quaternary basin. The damaged buildings are the consequences of several factors including strong ground motion, local site amplification, poor building workmanship and soil liquefaction. This last phenomenon occurred along the coastal Durrës bay into Quaternary marine sands (Q_4dt). To date, the conditions that triggered ground liquefaction and its consequences remain poorly understood.

Using existing site data and post-seismic observations, this study examines the conditions that may have triggered liquefaction along Durrës Bay. The analysis from soils properties reveals different liquefiable sandy and silty soils in the Q4dt formation. The simplified procedure based on geotechnical data indicates that the maximum ground acceleration (PGA) of 0.19g appears to be underestimated. Higher acceleration values could have been achieved due to seismic motion amplification effects associated with a shear wave velocity contrast located at the base of the Q4dt formation. Alternatively, another approach would tend to indicate that a sufficient number of cycles could have induced liquefactions without necessarily a PGA higher than 0.19g. However the latter result is based on the untested assumption that the ground motion recorded at the Durrës station can be transposed along the bay. The hypothesis of an acceleration higher than 0.19g along the Durrës bay remains the most plausible because of different soil conditions compared to the plain.

These results also raise the need to pay more attention about the seismic sequence, and, in particular, to the occurrence of strong foreshocks that can alter soil characteristics.

Keywords: liquefaction, Quaternary, sedimentary basin, Albania

INTRODUCTION

The Albanian November 26, 2019 earthquake with Mw magnitude of 6.4, considered as the strongest earthquake of the last 40 years in the region, hit the western part of the country. This region is located in the active Ionian–Adriatic thrust fault zone (Fig. 1A). The main shock was felt with an intensity IX degree (EMS-98) in the epicentral area and VIII-IX degree in Durrës (IGEWE, 2019a), and then decreased with distance from the epicenter. The location of the epicenter and fault source geometry remain uncertain and vary depending on the authors (e.g. Ganas et al, 2020; Govorčin et al, 2020; Papadopoulos et al, 2020). In particular, the values of hypocenter distance to Durres would range between 20 km and 40 km (Papadopoulos et al, 2020, IGEWE, 2019b).

The earthquake ground motion was recorded at various accelerometric stations of the Albanian network. Due to a power failure in Durrës accelerometer station (location Fig.1B), only the first 15 seconds of the main shock were recorded. The measured horizontal PGA values were 192 cm/s^2 for N-S component, 122.3 cm/s^2 for E-W component and 114.5 cm/s^2 for vertical component. The earthquake was reported to have lasted at least 35 seconds according to witness accounts in Durrës (Afps, 2019a). It occurred around one month after two strong foreshocks on 21 September 2019 (M_w = 5.1 and 5.6) and around 60 minutes after a magnitude 4.4 foreshock. Hundreds of aftershocks sequence with magnitude $M_L \geq 4.0$ lasted until 30 November (Lekkas et al, 2019a,

[1] Denis Moiriat, Ph.D., IRSN Institut de Radioprotection et de Sûreté Nucléaire

Duni & Theodoulidis, 2019). During the Dürres earthquake, the impacts were severe with 51 casualties and very heavy damages to structures in particular in Durrës city where 467 building were classified according to Eurocode 8-Part 3 as DS4 (significant damages) and DS5 (near collapse). The damages to the structures resulted from several factors including strong ground motion, local site amplification, poor building workmanship and soil liquefaction (Afps, 2019a, 2019b; Papadopoulos et al, 2020; EEFIT, 2020; Freddi et al, 2021).

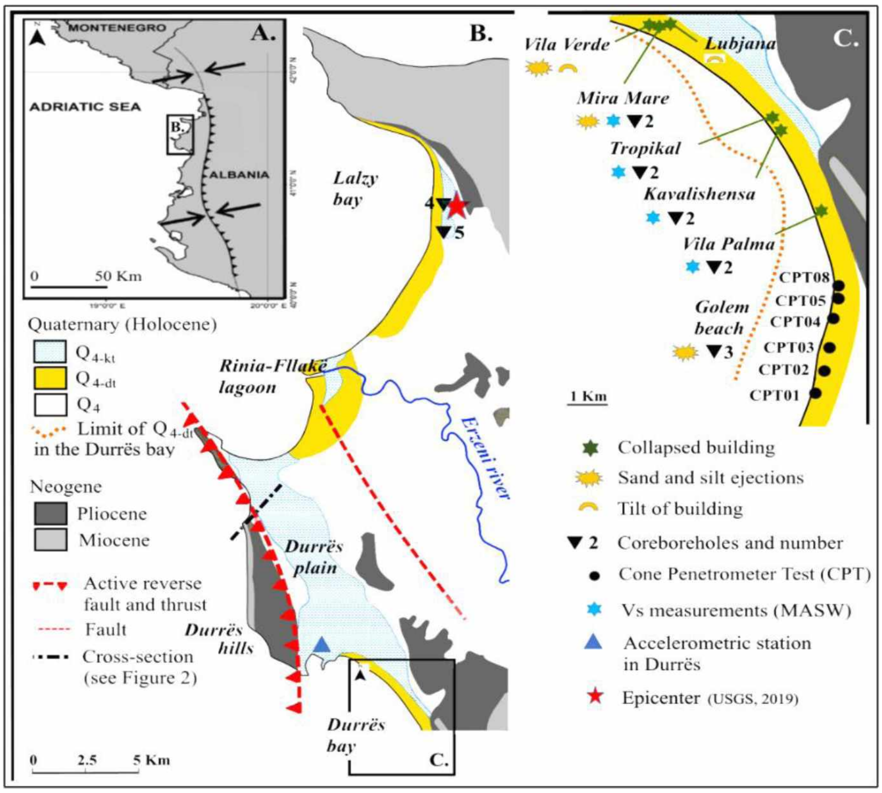

Figure 1 : Geological map of Durrës and study area

The inset 1A is extracted from Papadopoulos et al, 2020. This area is tectonically controlled by a thrust belt (toothed line in inset) associated with east-northeast—west-southwest compressional stress regime (arrows in inset). The simplified map 1B and the inset 1C derive from Geological map of Albania at 1:200 000 and 1: 100 000.

In this study we dwell on the conditions that trigger soil liquefaction. This phenomenon corresponds to a rapid drop in the soil strength with the build-up of water pressure within soils during ground shaking. It generally occurs in shallow loose Quaternary saturated sands or silty sands in the first fifteen meters of depth (Huang & You, 2013; Kavazanjian et al, 2016). Soil liquefaction below foundations may induce differential settlement, building tilting and even loss of bearing capacity with punching or tipping of structures (Seed & Idriss, 2003). Within days following the Durrës earthquake, several authors (Lekkas et al, 2019a; IGEWE, 2019a and Mavroulis et al, 2021) have notably observed sand and silt ejections near coastal areas along Durrës bay near collapsed buildings, Lalzy bay and the Rinia-Fllakë lagoon or in the Erzeni River floodplain (Fig 1B).
Regionally, ground motion would have likely been amplified due to soil conditions in water-saturated coastal plains (unconsolidated sediment) that are prone to liquefaction as suggested by Stein & Sevilgen, (2019) with their model of site amplification based on geologic mapping and in situ surveys of Vs_{30} (shear wave velocity averaged over the upper 30 m of the crust). However, other factors could explain the liquefaction triggering such as the earthquake duration which may drastically reduce the cyclic strength of soils. Indeed it turns out that a distant, long-lasting seismic event with an acceleration level rather low at the site can produce a large number of significant cycles capable to trigger the liquefaction phenomenon (IAEA, 2004; Wang & Manga, 2010). The impact of both strong foreshocks on 21 September 2019 with Mw 5.6 and Mw 5.1 which could have modified the soil behavior is also a plausible additional factor to consider.
This work focuses on the Durrës bay area where effects of liquefaction were observed at the surface. The first part of this paper presents the geological context of Durrës area. The methodology used in this work to evaluate the conditions prone to initiate the liquefaction phenomenon is depicted in a second part. The results and discussions about the main causes which could have triggered liquefaction are presented in a third part. The conclusions remind the main findings and limits of used methods.

1 GEOLOGICAL SETTING

On the western coast of Albania, the convergence associated with the continental collision is the cause of fold and thrust belt structures, mainly expressed by NNW-SSW striking anticlines and synclines. Located in the Ionian–Adriatic thrust fault-zone (Fig 1A), Durrës area belongs to Pre-Adriatic Depression characterized by thick sedimentary deposits mainly consisting of Neogene sediments composed of consolidated consolidated clay, marls, conglomerate and sandstone and covered by Quaternary deposits of different natures.
The Durres basin is tectonically controlled by an active synclinal (called Spitalla synclinal in UNEP report, 2001), which is overthrusted to the west by an active east-verging thrust fault (Mancini et al, 2020) located on the eastern limb of the Durres Mio-Pliocene anticline forming the Durres hills. The Spitalla syncline is located below the Durrës plain with a total sedimentary infilling of 240 m at least (UNEP report, 2001) including Quaternary deposits above clay and conglomeratic Neogene formation. The interpretative cross-section presented on the Figure 2 shows the different lithologies into the Durrës sedimentary basin. This cross-section is only of stratigraphic interest as it does not correctly represent the tectonic features in the west of the basin in particular (see Ganas et al, 2020; Mancini et al, 2020).

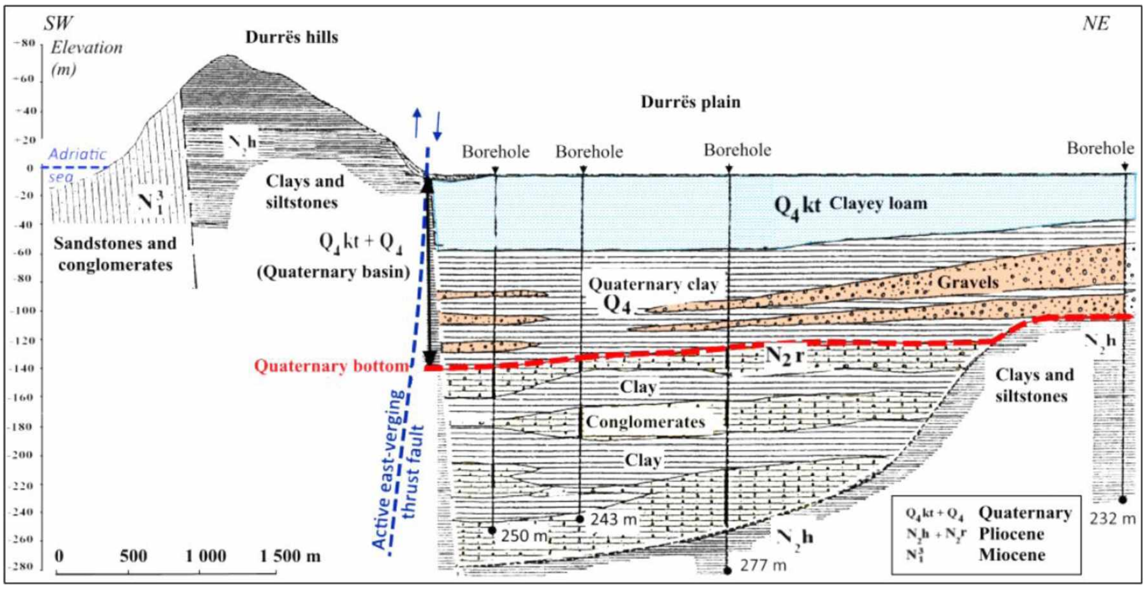

Figure 2 : Interpreted geological cross-section SW-NE of the Durrës sedimentary basin
Vertical scale strongly exaggerated (Extracted and modified from UNEP report, 2001; approximate location on the Figure 1).

In the Durrës plain, the Quaternary deposits are well developed with Holocene clayey loam deposits of fluvial and marshy origin with a maximum thickness of about 60 m (formation Q_4kt on the Fig. 2). Further down, the alluvial deposits (Q_4 on the Fig.2) constitute the lower part of Quaternary and are represented by intercalation of gravelly and clayey layers. The maximum thickness of Quaternary deposits under the Durrës plain would be about 130 m (Kociu et al, 1985). In the following paragraphs, we refer to the entire Quaternary fill above the Neogene formations as the "Quaternary basin" (Fig. 2).

Along the coastal zones (Fig. 1B and 1C), Holocene marine deposits (formation Q_4dt) overlays the alluvial deposits (Q_4) or the clayey marshy sediments (Q_4kt). The maximal thickness of Holocene marine deposits is around 50 m at the central zone of the bay, about 6 km south of the Durrës city and decreases toward the coasts to reach around 15 m of thickness on the inland coastline (UNEP, 2001; Simeoni et al, 2004 and Pano et al, 2005) where they constitute the main soil of foundations above the Q_4kt and Q_4 formations along Durrës Bay. They are then mainly characterized by fine, medium sands, silty sands, silty clay and mud interbedded . Some thin Quaternary deposits of colluvium origin are also developed on the Durrës hill slopes and represented by clayey to sandy deposits.

2 METHODOLOGY

In this paper, we assess the liquefaction occurrence according to different and complementary approaches presented hereafter.

We first review the soils conditions below foundations to assess the susceptibility of soils to liquefy or not in the first fifteen meters of depth. For this purpose, we have previously collected available geotechnical and geophysical data around some collapsed or damaged buildings along the Durrës bay (Fig. 1C). Most of these investigations were carried out few months after the earthquake at the beginning of the year 2020. Reports of these investigations are listed in the last section Data Sources at the end of this study (Albanese reports). They include 11 core boreholes with samples for soil properties identification (laboratory tests) and 4 MASW profiles (Multichannel Analysis of Surface Waves) providing shear wave velocity measurements (V_s) nearby collapsed buildings. Moreover, we collected previous geotechnical measurements from 8 Cone Penetration Test CPT (CPT01 to CPT08) carried out on the Golem beach are taken from Gashi (2016). It should be noted that the location of CPT06 and CPT07 and the measurement values for the CPT04 are not shown in the Gashi study (2016), therefore these three CPT are not included in this assessment.
All the collected investigations are located on the Figure 1C. Their distribution along the Durrës Bay covers roughly 10 km distance and allows to highlight the lithological variability of soils. In addition, the physical parameters are compared with those from boreholes drilled in the vicinity of Lalzy Bay beach closer to the epicenter area (location Fig. 1B) to give a broader view on the characterization of the Q_4dt formation.

In a second step, we investigated the influence of PGA parameter on the liquefaction initiation according to the simplified method detailed in Youd et al (2001) based on the approach developed by Robertson & Wride (1998) from the geotechnical CPT. This simplified method allows to provide a first reasonable preliminary assessment of the liquefaction potential of these soils in free-field conditions and from geotechnical tests carried out on the site. However, a numerical 1d effective-stress analysis would have been a more rigorous approach but generally requires the calibration of parameters used in the model with cyclic laboratory tests on the studied soils. In addition, the simplified method from geotechnical tests remains the state of art in current engineering practice (Kavazanjian et al, 2016; Afps, 2021)
For each depth, the ratio of the normalized cyclic strength resistance of soil (CRR_M) to the normalized mean stress generated by the earthquake of magnitude M_w (CSR_M) defines a safety factor (SF). As the method was initially built for earthquakes of M_w = 7.5, the SF is determined by considering the cyclic strength resistance of soil for an earthquake of M_w= 7.5 ($CRR_{7.5}$) and multiplied by a magnitude scaling factor (MSF) according to the Equation 1:

$$SF = CRR_{7.5}.MSF/CSR_M \text{ with } MSF = CSR_M/CSR_{7,5} \tag{1}$$

Classically the evaluation of $CRR_{7.5}$ is performed using in-situ geotechnical tests while the reference shear ratio generated by the seismic motion (CSR_M) is calculated at 65% of peak ground acceleration using the Equation 2:

$$CSR_M = 0.65.(PGA/g).(\sigma_{v0}/\sigma'_{v0}).\ r_d \tag{2}$$

With PGA: the peak horizontal ground acceleration, g: the acceleration of gravity, σ_{v0}: the total vertical stress, σ'_{v0}: the effective vertical stress and r_d: a reduction coefficient with the depth. The MSF recommended values for an earthquake with Mw < 7,5 should be necessarily chosen between two boundaries MSF_{min} and MSF_{max} defined by the Equation 3 with M_w the magnitude of earthquake:

$$MSF_{min} = 10^{2.24} / M_w^{\ 2.56} \text{ and } MSF_{max} = (M_w/7.5)^{-3.3} \tag{3}$$

The initiation of the liquefaction in a soil is triggered for SF < 1. Since liquefaction resistance of the soil increases quasi-proportionally with the depth, an overburden corrective factor K_σ was introduced according to the Equation 4 (Youd et al, 2001):

$$SF = CRR_{7.5}.MSF.K_\sigma/CSR_M \tag{4}$$

The factor K_σ is generally evaluated with the equations defined in Youd et al (2001) or Idriss & Boulanger (2008), knowing the effective vertical stress (σ'_{v0}) and the relative density of soils (Dr) which reflects the soil compactness.

Thirdly, the previous results are put into perspective regarding existing site conditions on the one hand along the Durrës bay, and on the other hand in the Durrës plain where the PGA value was recorded at the accelerometric station of Durrës (location Fig. 1B). In this part and thanks to MASW data and ambient noise measurements performed in Durrës (Duni et al, 2020 and Mancini et al, 2020), we study and discuss about possible effects of site conditions on the liquefaction triggering and, conversely, if the liquefaction occurrence could have modified the site conditions.

Fourth, we have sought to assess the impact of earthquake duration based, on the premise, that duration can be correlated as a first approximation to the number of cycles of earthquake. It exists different ways of counting the number of cycles and, in this study, we have considered the number of equivalent uniform stress cycles (N_E) which depends on the specified reference stress level taken to 65% of the peak acceleration as mentioned with the Equation 2. It can be computed either from different earthquake time series (Idriss & Boulanger, 2008) or throughout empirical correlations as N_E is function of the M_w magnitude, PGA and distance to the fault surface (Green & Terri, 2005; Hancock & Bommer, 2005; Idriss & Boulanger, 2008; Lasley et al, 2016). On the other hand, geotechnical laboratory tests (triaxial cyclic tests) provide the expression of normalized cyclic strength resistance of a soil at the onset of liquefaction as a function the number of cycles to induce liquefaction into the soils (N_L) with the Equation 5:

$$CRR = a.(N_L)^{-b} \quad (5)$$

With a et b both parameters depending on the nature of soils, its compactness and the effective pressure into the soils in particular. The Equation 5 depicts a liquefaction curve for a given soil that reflects the drop of the cyclic strength resistance with the increase of number of cycles.
After this, it is then possible to compare the cyclic stress generated by the earthquake (CSR_M) evaluated with the Equation 2 with the cyclic soil strength resistance for the magnitude M_w of the earthquake (CRR_M) estimated with the Equation 5 for $N_L = N_E$. The condition for the initiation of liquefaction is then given as soon as $CSR_M > CRR_M$.

3 RESULTS

3.1 Characterization of the formation Q_4dt with respect to liquefaction hazard

According to the geological logs of boreholes, the total thickness of Quaternary coastal deposits (Q_4dt) in Durrës bay or Lalzy bay is around 10 to 15 m above of the Quaternary clay. Among this 15 m thick series, the identification tests allow defining 4 main layers 1 to 4 below a backfill or topsoil layer thick up to 2 m on average in build-up areas. Their main characteristics are presented in the Table 1. The layer 1 corresponds to clayey or silty sands with a thickness could reach 5 meters in some places. The layer 2 stresses the difference between Durres and Lalzy bays with, along Durrës bay mixture of silty sands to sandy silts with a lot of horizontal variability and, in Lalzy bay two distinct levels of silty sands with one being much siltier at the bottom. Below layer 1 and 2, the soils become incrementally more clayey with clayey silt (layer 3) at first and silty clay more deeply (layer 4). Interbedded sands are still found into the layer 3.

This stratigraphy is confirmed by the study of Simeoni et al. (1996) for the seabed in the vicinity of the Durrës coast with an extension of layers 1 and 2 beyond 1 km from Golem beach (Fig. 1C). This vertical succession of layers or the horizontal variability in the layer 2 is also observed on the CPT logs. For these geotechnical tests, the Soil Behavior Type (SBT) allows classifying the soils according to their mechanical characteristics (Robertson, 2016) and its representation with depth illustrates a geotechnical stratigraphy (interpreted) presented on the Figure 3. The SBT is defined with the Equation 6:

$$SBT = [(3.47\text{-}\log Q)^2 + (\log F + 1.22)^2]^{0.5} \quad (6)$$

With Q and F the normalised tip and frictional resistance respectively and defined from tip resistance (q_c) and sleeve friction (f_s) measured along depth (Robertson, 2016). The results presented on Figure 3 point out that most of SBT values in the layers 1 and 2 are between 1.31 and 2.6 and cover the whole range of soils from clean sands to silts in the Robertson's soil classification (Robertson, 2016).

Table 1. *Characteristics of layers of the Quaternary formation Q_4dt*

Layer (based on ASTM classification)	Thickness (m) min-max	Median grain diameter d_{50} min-max	Content of clay % min-max	Content of silt % min-max	Void ratio min-max	Plasticity (PI %) (min-max)
Layer 1: silty or clayey Sands	1-4.9	0.15-0.23	< 15	< 20	0.7-0.9	
Layer 2 (Durrës bay): silty Sands to sandy Silts	5-8	0.01-0.15	6-29	2-42	0.5–1.1	5-15 for fine soils
Layer 2 (Lalzy bay): silty Sands	5-9	0.2-0.23	1-5	8-11	0.6	
		0.08-0.12	6-15	19-31	0.4-0.6	
Layer 3: clayey Silts	1.5-4		22-48	30-59		> 10
Layer 4: silty Clay	> 5		43-64	31-49	0.5-0.65	15-34

A relevant indicator for liquefaction occurrence is notably the state of compactness appraised with the relative density (Dr) which varies from 1 to 0 (or in percentage) and estimated in this study with a correlation from geotechnical CPT (Idriss & Boulanger, 2008) using Equation 7:

$$Dr = 0.478.(q_{c1N})^{0.264} - 1.063 \quad (7)$$

With q_{c1N} is the overburden corrected penetration resistance, dimensionless, depending on the tip resistance (q_c) measured during the cone test (CPT). The results presented on the Figure 3 indicate the existence of different loose levels more or less sandy or silty mainly in the layer 2, and thus susceptible to liquefy.

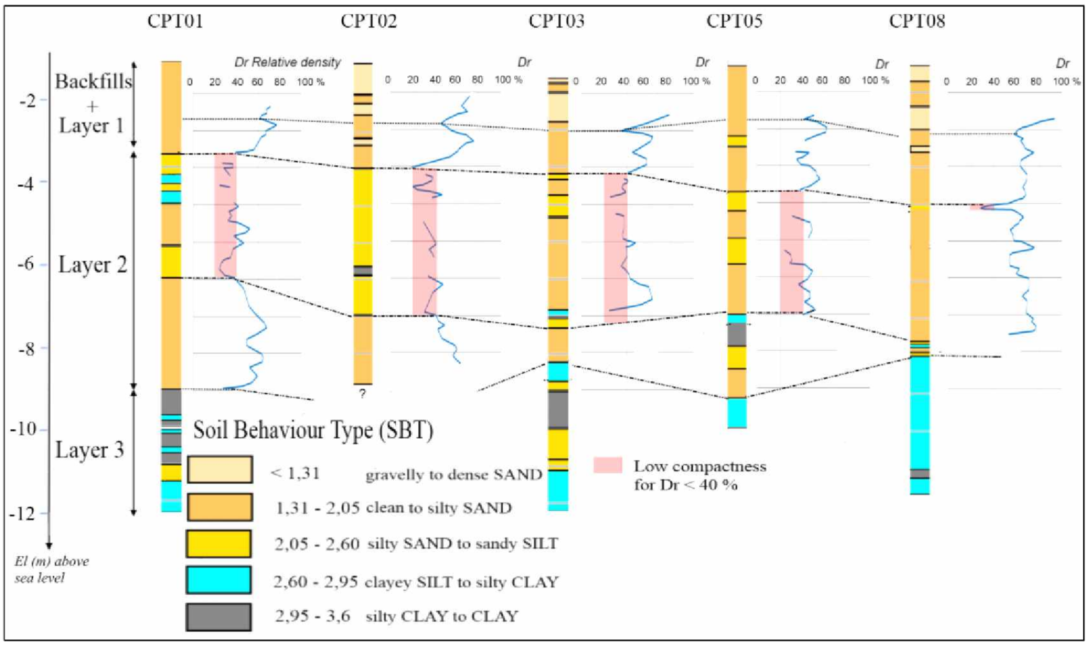

Figure 3 : Interpreted stratigraphy of the formation Q_4dt in the first ten meters of depth along Golem beach.

A second indicator of liquefaction susceptibility is provided by the low values of shear wave velocity (Vs) derived from MASW, especially those obtained less than 170 m/s in the first ten meters of depth under Mira Mare, Kavalishensa and Vila Palma. These values presented on the Figure 4 have been also supplemented by further V_s values derived from geotechnical tests CPT at Golem beach using the correlation developed for non-cemented Quaternary soils by Robertson (2015) from SBT defined with the Equation 6. These values derived from geotechnical tests confirm that the formation Q_4dt presents low V_s values also at Golem beach.

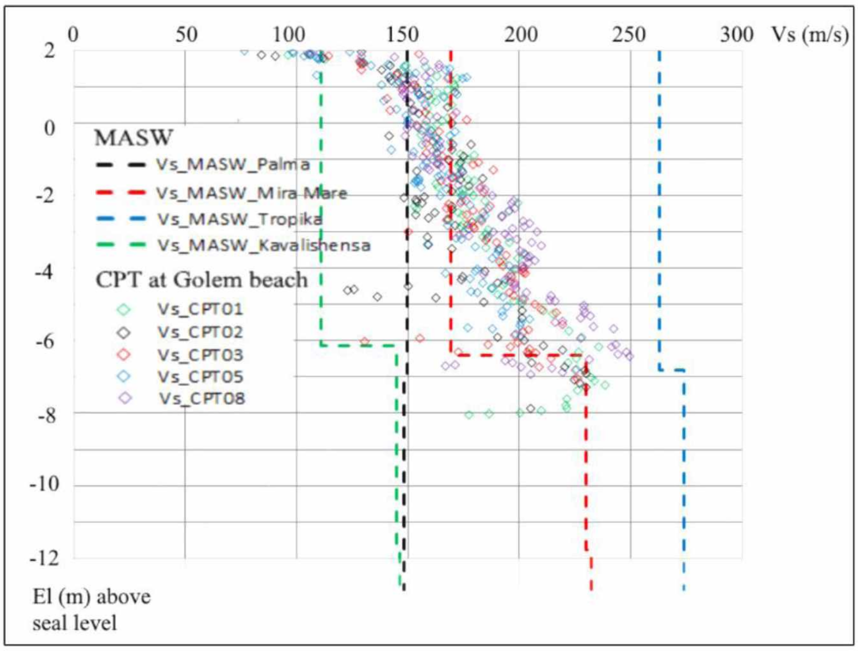

Figure 4 : Vs values in the formation Q_4dt versus depth

Other indicators for liquefaction susceptibility may also been deduced from the geological age, the soil permeability and the susceptibility criteria based on physical parameters as the grading curves or the Plasticity Index (PI).

Regarding the age, the Holocene age is a further indicator given that the soil liquefaction resistance increases in general with the geologic age: at ages greater than 2 Myr (pre-Pleistocene), the compactness and cohesion are such that the liquefaction susceptibility is generally zero to very low (Youd & Perkins, 1978).

Furthermore, the superficial aquifer connected to the Adriatic Sea has a level close to the surface in all the boreholes along Durrës bay and saturates the formation Q_4dt formation in consequence. The low values of vertical permeability values for the sandy and silty mixtures in the layer 2, about 10^{-6} m/s or in the range of 10^{-7} to 10^{-8} m /s when these soils are more clayey, are also propitious to raise water pressure during a cyclic loading.

In addition, the criteria based on the grading curves (Iai et al, 1986) allow to consider that the silty sands belonging to layers 1 and 2 but also the sandy interbedded into the layer 3 are liquefiable. The silty clay or clayey silts of the layers 3 and 4 could be considered as rather non-liquefiable soils with a Plasticity Index PI > 10 according to the Boulanger & Idriss (2006) criterion. For the other silty soils (clayey silts in the layer 3 or the sandy silts in the layer 2), it is difficult to evaluate their susceptibility to liquefy from simple rules based only on physical parameters (Atterberg limits, grading curves). Silty soils remain challenging soils to gauge and present an intermediate behavior between sand-like and clay-like, with rises of water pore pressure during the earthquake different than for sandy soils (Prakash & Puri, 2006).

Consequently, the analysis of all available data clearly highlights that layer 1, 2 and 3 include liquefiable fine sands and possible liquefiable silty materials.

3.2 Triggering of liquefaction according to PGA Values

In this assessment, the reference PGA value of 0.19g comes from the only available ground motion measurement in the area at Durrës station and was recorded during the first fifteen seconds of shaking before its shutdown. The PGA value along the bay may have been locally different due to soil conditions or due to a greater distance from the source. Therefore we conducted a sensitivity study with different PGA values and tested values between 0.15g and 0.4g to examine their influence on liquefaction occurrence in the Q_4dt formation. The SF calculations are based on the CPT at Golem beach. The assessment is carried out from the Equation 4 with minimal and maximal MSF values defined by Equation 3 to provide an uncertainty around the value of SF.

The results are similar for all CPTs and are presented for CPT01 on the Figure 5 (left). With a PGA < 0.2g, only some points or no points with SF < 1 are identified. With a PGA > 0.2g, some liquefiable materials appear in layer 1, 2 or 3. With a PGA = 0.3g, several meters of liquefiable levels are emphasized in the layer 2. With a PGA = 0.4g, almost the whole thicknesses of layer 2 and 3 are liquefiable. In this last case, the total mean liquefiable thickness reaches 8 meters.

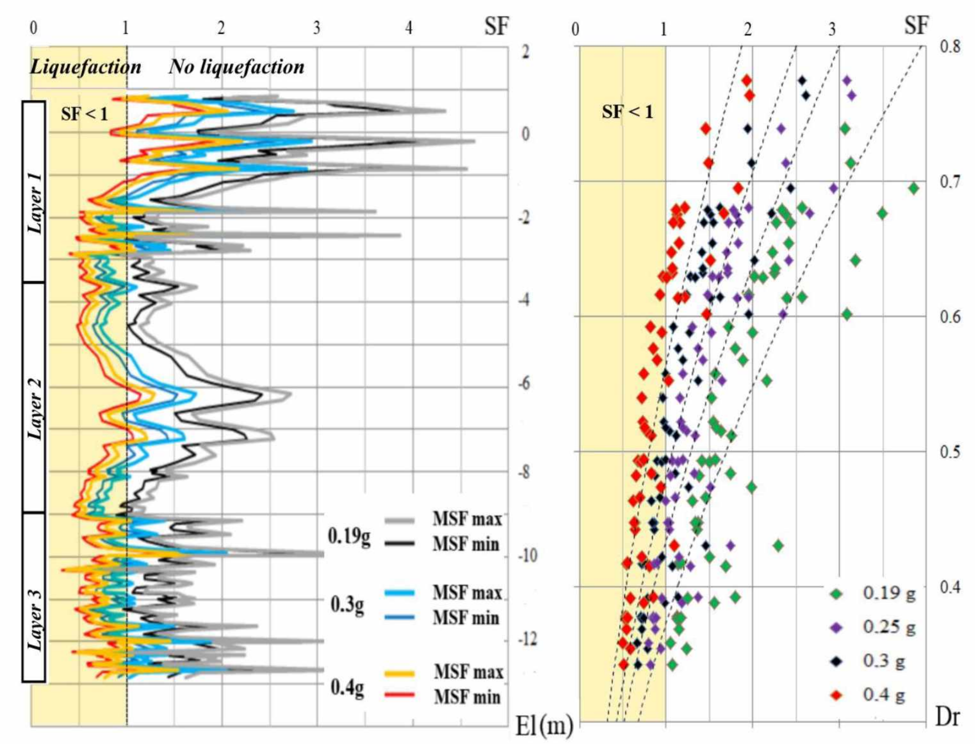

Figure 5 : Safety Factor for the CPT 01 versus depth (left) or versus relative density Dr (right) for values of PGA between 0.19g and 0.4g

These results are also corroborated with the distribution of SF with the relative density Dr between 0.3 and 0.8 presented on the Figure 5 (right). Only a few points or no points are liquefiable for a PGA = 0.19g whereas the soils are widely liquefiable with a PGA = 0.3g or concern all soils with Dr > 0.6 for a PGA = 0.4g. As a remark, a further calculation with a level of the groundwater close to the surface doesn't change the findings of these results.

3.3 Influence of local geological site conditions

In this part, we have investigated whether the local site conditions along Durrës bay could have increased the acceleration to trigger the liquefaction. In this regard, we have compared the site conditions on the one hand below the accelerometric station in Durrës plain which didn't present any evidence of liquefaction at the ground surface after the main shock (Afps, 2019a, b), and on the other hand along the Durrës bay where the soils of the formation Q_4dt were liquefied.

These different site conditions can be highlighted through the V_s profiles with depth and the frequency peaks on the HVSR curves (Horizontal-to-Vertical Spectral Ratio) computed from ambient noise measurements. This geophysical technique is usual to retrieve the soil fundamental resonance frequency which can be related to the presence of a seismic velocity contrast in depth. Duni et al (2020) and Mancini et al (2020) have measured this frequency (f_0) along Durrës bay in particular.

3.3.1 Site conditions below the Durrës accelerometric station located in Durrës Plain

The station in free-field conditions (located on the Fig. 1B) is installed on soft soil formations Q_4kt of the Durrës plain in the southwestern part of the sedimentary basin (Duni & Theodoulidis, 2019). Three further geological and geophysical investigations reports including additional MASW profiles in Durrës plain were collected to have a better overview of site conditions around the station. These MASW profiles are presented and located on the Figure 6 and referenced in the last section Data Sources of this study (Albanese reports).

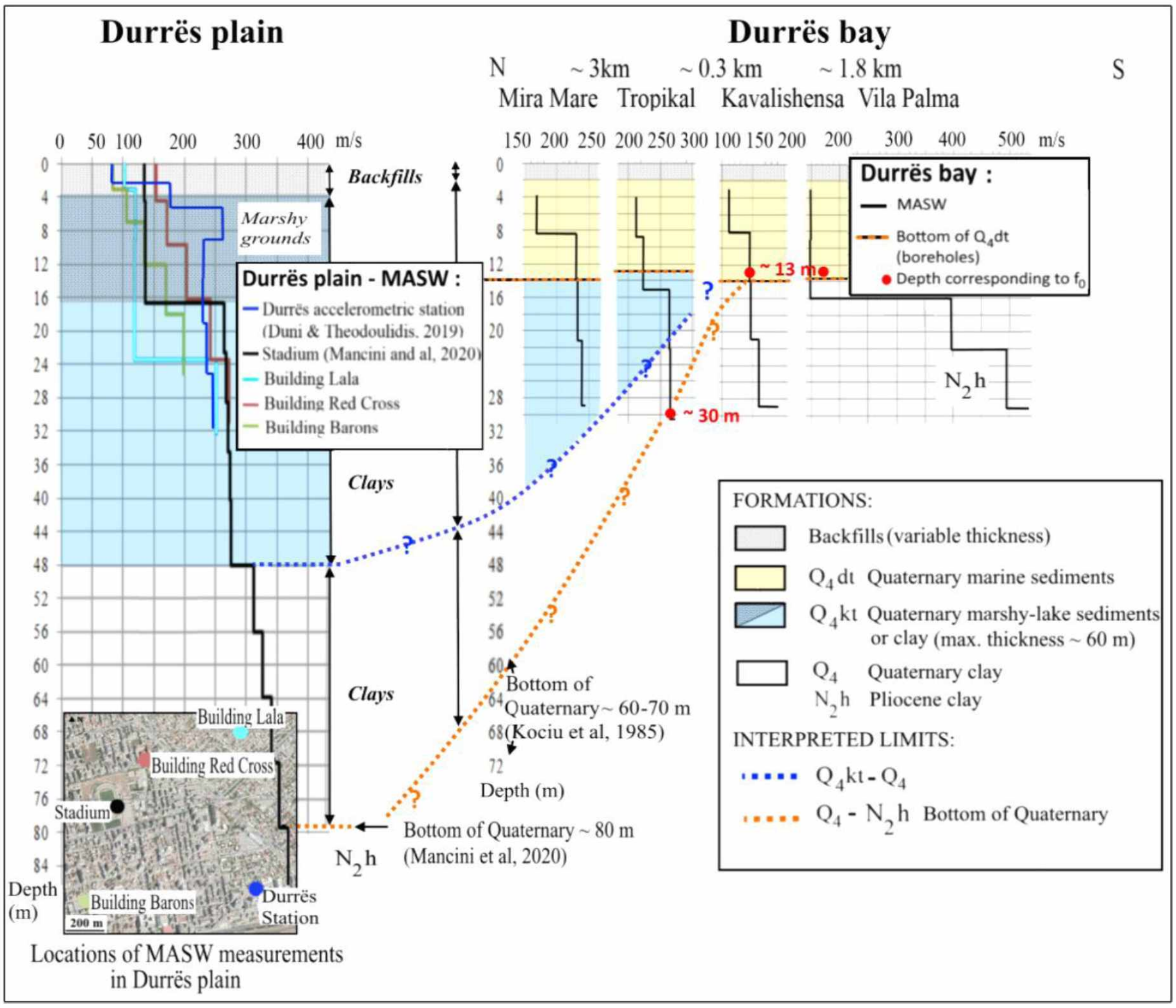

Figure 6 : Site conditions below Durrës plain and along the Durrës bay

In the range of depth 0 - 25 m around (subsurface conditions), all the Vs values are less than 270 m/s and their distribution with the depth indicate stratigraphic variations confirmed with the core samples. The backfills with a thickness varying between 0.5 to 5 m overlay mainly different thick clayey layers (Holocene, Q_4kt), including thick soft clay with low $V_s \leq 150$ m/s and which reach 17 or 23 m of depth below the building "Lala" or the stadium respectively. Those soft sediments correspond to former marshy soils in the first ten meters and are well developed further east of the Durrës plain. Those marshlands have been artificially drained and backfilled in the past and present a current ground subsidence with vertical settlements from some millimeters to 2.5 cm/year in the central part of the Durrës plain (Bedini, 2019). Despite their young age (Holocene) and their low Vs values, these subsurface clayey layers below the backfills can be considered no susceptible to liquefy as a result of their cohesion in particular. From identification laboratory tests (presented in Albanese geotechnical reports in Data Sources section), a complementary analysis indicates that their physical properties in the first ten meters of depth meet the criteria for fine soils improper to liquefy, either a content of size particle with a diameter $d \leq 74$ µm upper than 20 % and a Plasticity Index PI > 12 (Seed et al, 2003) or W < 0.8 LL with W the natural water content and LL the limit of liquidity (Bray & Sancio, 2006).

Below 25 m of depth around, mostly Vs values are in the same range around 250-300 m/s and correspond to stiffer Quaternary clay of the formation Q_4kt or Q_4. The bottom of Quaternary has been estimated below the

Durrës station around 80 m depth above Neogene formations from geophysical investigations (Mancini et al, 2020). This limit is shallower than the depth around 130-140 m for the bottom of Quaternary obtained from boreholes (UNEF, 2001) or other geophysical measurements (Kociu et al, 1985). This difference could be explained by the geometry of Quaternary filling with Neogene presented in Kociu et al (1985).

3.3.2 Site conditions along Durrës bay

In this area, the frequency peaks (f_0) measured by Duni et al (2020) and Mancini et al (2020) are higher than in the vicinity of the accelerometric station and present a regular increase from north below Mira Mare ($f_0 \approx$ 0.95 Hz) to south below Vila Palma ($f_0 \approx$ 3 Hz). As this peak may not necessarily correspond to a single geological interface, we first estimated the depth of the interface corresponding to f_0 using the classical formula depicted by the Equation 8 (Ibs-von Seht & Wohlenberg, 1999):

$$h \approx V_{s,h} / 4.f_0 \quad (8)$$

with $V_{s,h}$ the average velocity estimated from available MASW profiles at the depth h according to the equation (9):

$$V_{s,h} = h / \sum h_i/V_{s,i} \quad (9)$$

With h_i and $V_{s,i}$ the thickness and the $V_{s,i}$ value respectively in each layer at each location. Some values of h are presented on the Figure 6. The frequency peaks correspond to either the bottom of the formation Q_4dt below Kavalishensa and Vila Palma buildings or a deeper geological interface below Tropikal hotel (Fig.6).

3.3.3 Discussion about the influence of local geological site conditions

On the contrary of the results for Durrës plain, the results along Durrës bay show that the frequency peak (f_0) can correspond to a subsurface seismic contrast at the bottom of formation Q4dt. This reflects a possible site effect into this marine formation and, thus, possibly an acceleration upper than the measured values at the Durrës station.

The h value computed from Eq. 8 around 30 m of depth below Tropikal hotel (Fig.6) could match the Quaternary bottom limit depth with the Neogene clay (N2h). This stratigraphic limit depth between Quaternary and Neogene decreases inversely to the increase of peak frequency (f_0) from north of the bay around 60-70 m below Mira Mare to the south of the bay around 10-20 m below Vila Palma (Fig.6). Hence, as the liquefaction occurred at different places along the bay, these variations of the Quaternary thickness do not appear to have had an influence on the initiation of the liquefaction into the formation Q_4dt.

Moreover, the soft rocks recognized in a drilling below 32 m depth at Golem beach, reveal that the part of the bay corresponds to the eastern edge of the Quaternary infilling of the sedimentary basin (Fig. 6). It is also noticeable on the Figure 1C with the outcrops of Neogene (N2h) to the east underlining the limit east of the Quaternary basin. This proximity with a basin's edge could have locally led to waves interferences in the formation Q_4dt with the conversion of body waves in surface waves which then propagate across the basin (Hancok & Bommer, 2005). In this regard, the spatial distribution of most impacted buildings DS4 and DS5 in Durrës city tends to indicate two preferential impacted zones close to basin's edges (Afps, 2019a, b): one at the west developed along the contact between the easterly Neogene formation and the Quaternary infilling of the Durrës basin, and another one at the east of Durrës and extended along the Durrës bay.

Nevertheless, there are others causes that could explain this distribution of damages in particular along Durrës bay. The resonance phenomenon with the buildings is also suspected for the concrete framed building of 5-7 storeys distributed along the seashore (Afps, 2019a, b). This effect may occur when the frequency content of the earthquake is particularly rich in a frequency band close to both soils and the structure natural frequencies. For concrete framed buildings the fundamental period of vibrations, based on EC8 recommendations, can be calculated using the Equation 10 with H the height of building:

$$1/f \approx 0.075.H^{3/4} \quad (10)$$

Assuming a mean height of 3.5 m per storey, the range of fundamental frequencies of the buildings would be around between 1.2 and 1.55 Hz. These values are only found locally for the frequency peaks (f_0) along the bay (Duni et al, 2020; Mancini et al, 2020) and therefore cannot explain the occurrence of the resonance phenomenon all along the bay. However, as the seismic response is strongly affected by the soil stiffness, the presence of liquefied soils during the earthquake also affects this response. Indeed, the increase of pore water pressure in soils tend to decrease the peak frequency (f_0) when the soil is very close to the initiation of liquefaction or well liquefied (Kramer et al, 2016). Thus, the resonance phenomenon could have been involved as a consequence of softening associated with the initiation of liquefaction in the formation Q_4dt.

3.4. Influence of the earthquake's duration on liquefaction occurrence

The impact of the earthquake duration on the triggering of the soil liquefaction is not generally considered or even discussed in engineering practices where the evaluations remain based on the simplified method (Youd et al, 2001). This simplified method integrates indirectly the number of cycles through the magnitude scaling factor (MSF) which could be expressed according to the Equation (11):

$$MSF = CSR_M/CSR_{7.5} = (N_{E\ 7.5}/N_E)^{\ b} \quad (11)$$

where $N_{E\ 7.5}$ and N_E are the numbers of equivalent uniform cycles for M_w = 7.5 and M_w the magnitude of the studied earthquake respectively and b an exponent depending of the nature of soils (Boulanger & Idriss, 2015). Value $N_{E\ 7.5}$ is traditionally equal to 15 cycles (Seed & Idriss, 1982) and as a result, the values of N_E can easily be derived from the Equation (11) if b and MSF are known. However, the standard value $N_{E\ 7.5}$ = 15 for an earthquake of M_w = 7.5 can be widely questioned. In addition, the exponent b relying on both nature and relative density of soil (Dr) complicates the evaluation of N_E notably in the presence of silt and sand mixtures with a variable relative density (Dr) as in the Q_4dt formation. That's why in this study, we propose to evaluate N_E directly from earthquake time series and, then, to compare the CRR and CSR.

3.4.1 Estimation of number of equivalent uniform stress cycles (N_E) for the main shock

Due to a power outage in Durrës station 15 seconds after the arrival of the first seismic waves of the main shock, it was not possible to evaluate completely the N_E value for the Mw 6,4 Durres earthquake from records provided by IGEWE (2019b). Accordingly we have used different approaches to estimate a tangible value.

At first approximation, we have considered beforehand, that the ground motions recorded to the Durrës station located on backfills above the formation Q4kt could be transposed along Durrës bay where the soils foundations are backfills and then the formation Q_4dt. While the nature of soils may change the amplitude of the motions at the surface, the number of cycles remains approximately the same indeed, with only the high frequency cycles filtered out by the increase of soil damping (Hancok & Bommer, 2005).

In a second approximation, the simple method presented in Idriss & Boulanger (2008) has been used to estimate the number of cycles N_E from the different earthquakes recorded to the Durrës station (IGEWE, 2019b). Two examples are shown on the Figure 7 where the N_E value corresponds to the sum of all values upper than the absolute value of 65% of maximum acceleration (a_{max}). The counting is done for positive and negative accelerations and provides minimal and maximal values.

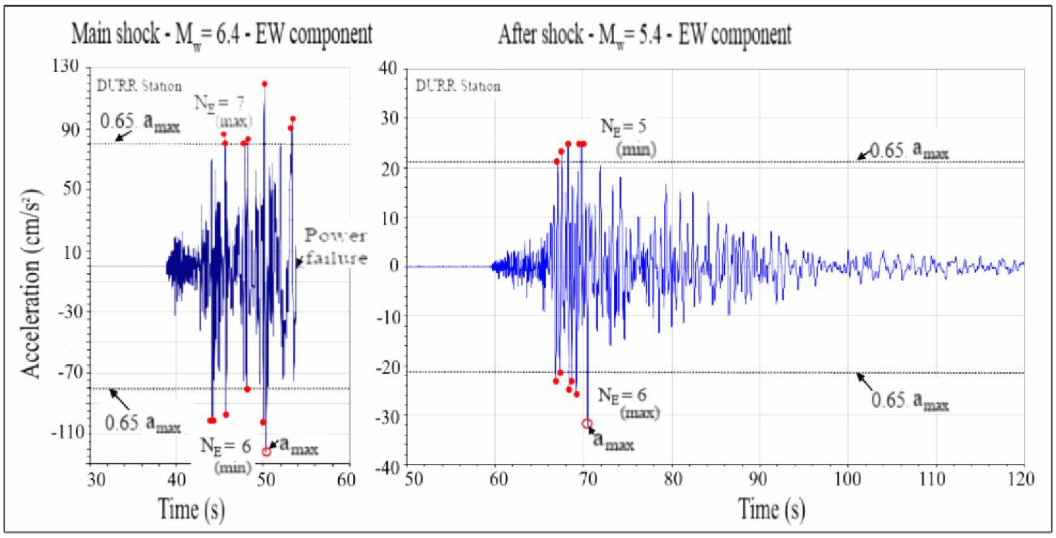

Figure 7 : Number of equivalent uniform stress cycles (N_E) for the main shock M_w 6.4 (left) and for an aftershock M_w 5.4 (right) recorded the same day to the Durrës station – Component EW –

All the results are presented in the Table 3 and compared to the bibliography for same magnitude and hypocentral distance (called R hereafter). In the analysis, only horizontal components (EW and NS) have been considered as the liquefaction mechanism mainly acts as a shear mechanism.

For the main shock, the few estimated values from earthquake time series recorded to the Durrës station imply $N_E \geq 7$ with a R distance to Durrës varying according the authors between 17 and 41 km (IGEWE, 2019b; Papadopoulos et al, 2020). Although recordings at other stations can't be compared due to different geological contexts and azimuth with respect to the epicenter, the number N_E for the main shock is counted between 7 and 8 for the horizontal N-S component in Tirana station with a R distance around 30 km, the closest station to the Dürres epicenter after the Dürres station. Furthermore, the bibliography for equivalent magnitude Mw = 6.3 or 6.4 and R distance between 20 and 40 km provides minimal $N_E = 10$ and maximal $N_E = 14$.

The aftershocks recorded at the Durrës station may also provide relevant information about the variability of N_E values, the influence of R distance and the similarities between the results.
For the aftershocks with Mw = 5.3 or 5.4, N_E values are between 6 and 11 with R distance between 40 and 60 km. The bibliography for equivalent magnitude and R distance indicates N_E values between 8 and 14. Accordingly, for a greater R distance and a lower magnitude, these N_E values are comparable enough to these for the main shock between 7 and 14. For both aftershocks with $M_w = 4.7$, N_E values are significantly less than 5 with a R distance between 30 and 40 km and present clear difference with the N_E values for a magnitude $M_w > 5$. Moreover, a lower bound for liquefaction could be considered to $M_w = 5$ (Green & Bommer, 2019). Consequently, a probable limit for liquefaction occurrence in the Durrës context could be given for $N_E < 5$.

In that respect and since N_E values increase with the R distance, conservative N_E values for the main shock can be considered between 7 and 10 with R distance around 20 km and between 10 and 14 for R distance around 40 km.

Table 3. *Values of equivalent uniform stress cycles (N_E) for the main shock and four aftershocks*

Range of magnitude Mw	Earthquake	Date	Hour (UTC)	Hypo. distance (R in km)	M_w	Comp.	N_E min	N_E max
$6 < M_w < 7$	Main shock - Durrës station during ~15 s	11 26	02h 54	17 or 41	6.4	E-W	7	?
						N-S	3	?
						Z	8	?
	Bibliography (Green, 2001)			20 to 40	6.4		10	14
$5 < M_w < 6$	Aftershocks - Durrës station	11 26	6h 08	48	5.4	E-W	5	6
						N-S	8	10
		11 27	14h 45	62	5.3	E-W	8	9
						N-S	10	11
	Bibliography (Green, 2001)			40 to 60	5.4		≥ 8	
	Bibliography (Lasley et al, 2016)			40 to 60	5.5		12	14
$4 < M_w < 5$	Aftershocks - Durrës station	11 28	10h 52	38	4.7	E-W	2	3
						N-S	2	2
						Z	4	6
		11 26	13h 05	33	4.7	N-S	3	4

3.4.2 Comparison between the cyclic stress due to earthquake (CSR) and the cyclic resistance of soils (CRR)
This comparison is focused on the main thickness of liquefiable materials located in the layer 2 and composed of mixtures of sand and silt, either silty sands or sandy silts with variable clayey content.
The cyclic behavior of this kind of soils is generally to understand and depends on both the ratio between sands and silts contents and the nature of fines (Jradi, 2019; Enomoto, 2019). Notably and for a same void ratio, the cyclic resistance of soils decreases generally with the increase of silt content up to around 35 % and then increases afterwards beyond 40 % (Polito, 1999). Therefore, making an adequate comparison between the

stress generated by the earthquake (CSR) and the cyclic resistance of these silty soils (CRR) remains a difficult problem without a good knowledge of the cyclic behavior of these materials.
Furthermore, even if their liquefaction curves of these materials (represented by the Equation 5) were sufficiently well depicted, it is not certain that they reflect the overall behavior at the scale of the entire liquefiable layer due to the large variability of these materials both in nature and in soil compactness (Fig. 3). Despite all these limits, we have looked at liquefaction curves derived from laboratory tests in the bibliography about mixtures of sands and silts (Benghalia et al, 2011; El Takch et al, 2016; Jradi, 2019; Enomoto, 2019) which may correspond to sandy and silty mixtures of layer 2 with both a mean equivalent compactness (Dr) between 0.25 to 0.5. Chosen examples are presented on the Figure 8 to compare, at the same effective confining pressure (σ'= 105 KPa), the CSR and the CRR when the number of cycles to liquefy (N_L) corresponds to the number of equivalent uniform stress cycles due to the main shock (N_E). Two ranges of N_E values are studied according to the uncertainties about the hypocentral distance (R), either R ~ 20 km (pale grey Fig. 8) or R ~ 40 km (darker grey Fig. 8).

For a PGA = 0,19g (hypothesis n°1 for the mainshock on the Fig. 8) and R ~20 km, mixtures of sands and silts are liquefied (CSR > CRR, red area with N_E between 7 and 10 on the Fig. 8) and are more likely to be liquefied for R ~ 40 km (CSR > CRR, red area with N_E between 10 and 14 on the Fig. 8). This tends to show the more severe impact of a distant earthquake with a higher number of cycles on the triggering of liquefaction. The high N_E values may be related to either the earthquake duration or the hypocentral distance (R). Another less obvious cause could be the nature of soils of the formation Q_4dt which may filter out less the cycles of high frequencies than the formation Q_4kt. In this case, the ground motions recorded at the Durrës station cannot be transposed along Durrës bay.

For a PGA = 0,3g (hypothesis n°2 for the mainshock on the Fig. 8), the seismic stress CSR is always higher that the CRR (cross-hatched area on the Fig. 8) and this confirm the previous finding with the simplified method from geotechnical data (Fig. 5) that most mixtures of sands and silts in layer 2 of the Q_4dt formation are liquefied with a PGA = 0.3g.

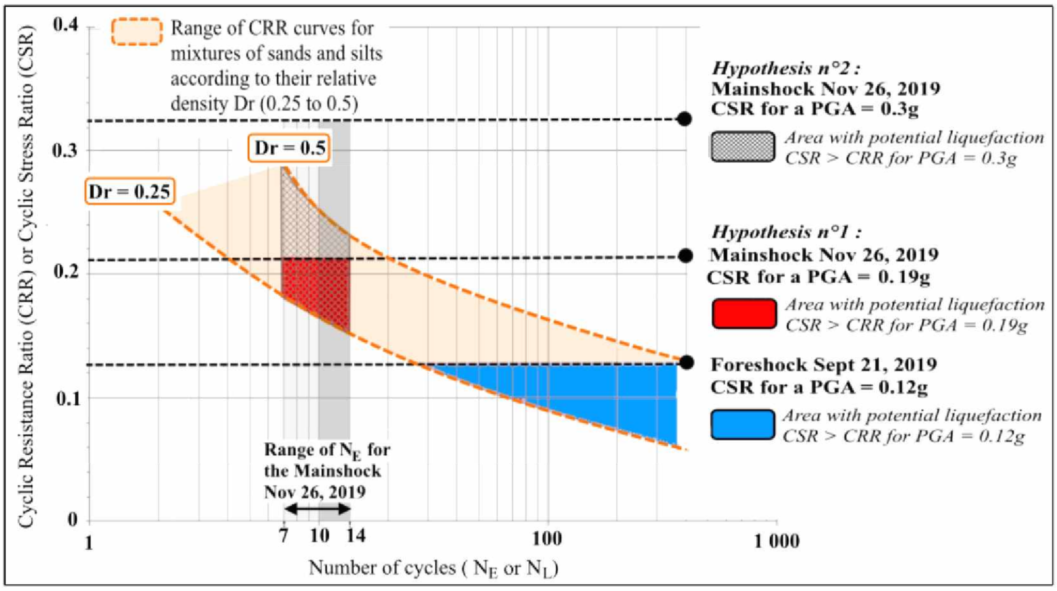

Figure 8: Comparison between the CRR and the CSR at σ' = 105 KPa for different PGA values

3.4.3 Discussion about the influence of two strong foreshocks on 21 September 2019 (Mw = 5.1 and 5.6)
After the two strong foreshocks on 21 September 2019 (M_w = 5.1 and 5.6) with epicenters located around 10 km north of Durrës city and low PGA values of 0.1-0.12g at the Durrës station (Freddi et al, 2021; Vittori et al, 2021), some rare liquefaction ejections of sand and water as well as small scale subsidence were observed in the north of Durrës bay (Lekkas et al, 2019b). However, for a PGA = 0.12g, these liquefaction occurrences cannot be explained with the simplified method from geotechnical in-situ tests (see Fig 5) or only with significant and unrealistic N_E values for an earthquake of magnitude lower than 6 ($N_E \geq 30$, blue area on the Fig. 8 for a PGA = 0.12g). This is either due to the limitations of these simplified approaches or because, as

mentioned before, the ground motion recorded at the Durrës station might not actually be transposed along the bay of Durrës due to the different nature of the soils between the bay ($Q4_{dt}$) and the Durres plain ($Q4_{kt}$).

Moreover, the occurrence of these 2 foreshocks may have modified the local soil conditions during the mainshock. Indeed, Bonilla et al. (2019) have shown from earthquake records in Japan how strong ground motion can significantly decrease the soil shear modulus during the co-seismic phase. They also show that the soil gradually tends to recover its initial properties. In the case of Albania, the water overpressures generated in soils during the shaking of both foreshocks may not have been totally dissipated 2 months later due to low soil permeability in the Quaternary formation Q_4dt (range from 10^{-6} m/s to 10^{-8} m /s in the clayey soils). Therefore, the main shock on 26 November 2019 could have induced liquefaction into soils with lower cyclic resistance (CRR) due to previous foreshocks.
However, the shaking effects during foreshocks could have degraded the soil resistance to liquefy (CRR) as much as improved it according to cyclic triaxial tests results on a sand of Dr = 0.45 under a confining pressure of 50 KPa (Nelson & Okamura, 2015). It would actually depend on the shear strain reached during the foreshocks that would or not exceed a specific threshold (Nelson & Okamura, 2015; Okamura et al, 2019). In addition, if there was liquefaction on 21 September 2019 in the Q_4dt formation, this may have led to antagonistic effects on the CRR curves with a soil's densification and change in the soil fabric according to other results on other sands (Ye et al, 2018; Wang et al, 2019). Nevertheless, it is unclear whether these results are applicable to mixtures of sands and silts of Quaternary formation Q_4dt. Moreover, the liquefaction occurrences on 21 September 2019 remain very localized and sparse as mentioned in Lekkas et al (2019b) and thus, without inducing any subsequent soil reconsolidation.
Laboratory investigations on the soils of formation Q_4dt would allow to confirm the hypothesis during the main earthquake of a lower resistance (CRR) due to the occurrence of two strong foreshocks with $M_w > 5$.

CONCLUSIONS

Several complementary approaches using different geological, geophysical and geotechnical data have been studied to review the conditions which caused liquefaction occurrences along Durrës bay in Quaternary marine formation (Q_4dt) consecutive to the Albanian November 26, 2019 earthquake with M_w magnitude of 6.4. The main findings are:

1. The characterization of the Quaternary marine formation (Q_4dt) reveals liquefiable fine sands and silty materials with low compactness and low mechanical properties or Vs values.
2. The classic simplified procedure to evaluate the triggering liquefaction from geotechnical data points out that the PGA value to 0.19g recorded to the free field accelerometric station located in the Durrës plain is not sufficient to induce the observed liquefaction phenomena at the surface along Durrës bay. However the simplified method has strong limitations, notably because earthquake information is limited to PGA and M_w, the impacts of the ground motion frequency content and duration could not be taken into account. A numerical 1d effective-stress analysis would have been a more rigorous approach but this alternative approach requires in particular the calibration of parameters used in the model with laboratory tests on the studied soils (cyclic tests).
3. The study of site conditions along Durrës bay stresses a possible site effect due to seismic contrast at the bottom of formation Q_4dt which could explain a probable higher acceleration than in Durrës plain. The proximity of the interface between the Quaternary and the Neogene series to the east of Durrës city could have also played a role in modifying the ground motion locally.
4. The approach to evaluate the impact of the earthquake duration by the number of cycles remains a difficult question because the number of cycles also depends in particular on the hypocentral distance (R). A simplified approach based on estimates of the number of equivalent uniform cycles (N_E) and the assumption that the ground motions recorded at the Durrës station (Durrës plain) may be transposed along the Durrës bay, would tend to show that for a PGA =0. 19g, the mainshock could have been sufficient to liquefy the soils of the Q4dt formation if the hypocentral distance was large enough to induce a large number of cycles and/or if the state of soils was altered after the occurrence of two strong foreshocks on 21 September 2019 (Mw = 5.1 and 5.6).
   However, it is also likely that the ground motion recorded at the Durrës station is not representative of the earthquake intensity across the coastal region due to the different nature of the soils between the bay and the Durrës plain. The assumption of a higher acceleration than 0.19g along the Durrës Bay remains the

most plausible, which is confirmed by all simplified approaches either from simplified geotechnical tests or from estimates of the number of equivalent uniform cycles N_E.

This comparative study underlines both the difficulties to identify the specific causes that trigger soils liquefaction and the limits of different methods to evaluate liquefaction hazard. These results emphasize also the need to take uncertainties into account in the different parameters used in each method and the implementation of different methods to explore uncertainty. In addition, it raises the question of the need to pay more attention about the whole seismic sequence of an event in the understanding of the liquefaction phenomena due to the possibly altered state of soils after strong foreshocks notably. At last, it shows the importance of collecting data, such as strong ground motion recordings, local soil characterization, in situ geological, geophysical and geotechnical measurements, laboratory tests, and post-seismic observations.

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